A Multivariate Statistical Approach to Characterizing Impacts from Combined Sewer Overflows Using Regional Chemistry Data

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Abstract
To satisfy requirements in the City of Seattle's NPDES permit, a CSO characterization project was designed to predict the chemical and bacteriological quality, and ultimately the potential impact on receiving water quality, of Seattle's CSO discharges using data from CSOs in other Northwest municipalities. Statistical evaluations were performed to identify relationships between the chemical concentrations in CSOs in these municipalities and explanatory variables such as land use, the percentage of sewage in the CSO effluent, and the number of rainstorm-free days prior to the CSO discharge. Land use was the most important explanatory variable for chemical concentrations. Of the five chemicals of concern examined quantitatively (copper, zinc, bis(2-ethylhexyl)phthalate, phenanthrene, and fluoranthene), only copper had a reasonable potential to exceed ambient WQC at the end of the pipe.

Introduction
The City of Seattle's combined sewer system (CSS) is one of the largest in the northwestern United States. Freshwater receiving water bodies include Lake Washington, Lake Union, Green Lake, Union Bay, Portage Bay, Salmon Bay, Longfellow Creek, and the Lake Washington Ship Canal. Marine receiving water bodies include Elliott Bay, Puget Sound, and the Ship Canal west of the Locks. Most of these water bodies have documented water quality problems, as evidenced by their inclusion on the State of Washington's 1998 303(d) list for water-quality-limited water bodies. Most of the documented exceedances in surface water are for fecal coliform bacteria. Elevated chemical concentrations in sediment from the Duwamish River, Elliott Bay, and Puget Sound are also described on the 303(d) list.

Most of the combined sewer outfalls that are monitored discharge at least occasionally. During the period January 1997 through March 1999, more than 500 separate discharge events were monitored, totaling more than 250 million gallons discharged. The volume per event was quite variable, ranging from 2 to approximately 15 million gallons. The two combined sewer overflows (CSOs) that discharged most frequently during this time period are Magnolia and Duwamish Diagonal. These two CSOs have each discharged approximately 90 times in the last 2-plus years. The remainder of the top 10 CSOs, with respect to discharge frequency, empty into Lake Washington.

Seattle Public Utilities (SPU) is responsible for maintaining and monitoring the CSS under a National Pollutant Discharge Elimination System (NPDES) permit issued by the Washington Department of Ecology (Ecology). One of the requirements of the permit is to produce a Characterization Monitoring and Modeling Study of CSOs. The main objectives of the CSO characterization project were as follows:

- Predict the chemical and bacteriological quality, and ultimately the potential impact on receiving water quality, of Seattle's CSO discharges, using data from CSOs in other municipalities in the Northwest
- Determine whether there is any evidence that environmental impacts, primarily in sediment adjacent to outfalls, can be attributed to CSOs

The work reported here describes the water quality portion of the project. The sediment quality portion of the project is described in EVS (2000).

Methods

Study Design

The City of Seattle has not collected any water quality data for its CSOs within the last 15 years. Consequently, pollutant data from CSOs in other regional municipalities were used to characterize current conditions. Existing data were compiled into relational databases (Paradox v. 8.0, Corel Corporation) for the following five subjects:

- Water quality data (e.g., chemical and bacteriological characteristics of discharges)
- Sample characteristics (e.g., type of sampler, proportion of discharge sampled)
- Percent sewage in discharge (calculated by measuring sewage tracers such as caffeine and ammonia)
- Discharge characteristics (e.g., duration and volume of discharge, associated rainfall, days since rainfall)
- Drainage basin characteristics (e.g., drainage basin area, land use)

Data on these subjects were available from the City of Seattle (discharge and outfall characteristics only), King County, the City of Bremerton (WA), and the Greater Vancouver (BC) Regional District (GVRD). The compiled data from the other municipalities were used in various multivariate statistical analyses to determine whether derived algorithms could predict CSO water quality (see Statistical Methods below). Impacts to receiving water were analyzed based on a review of water quality data, predicted CSO water quality data, and water quality criteria.

Data Sources and Data Reduction Methods

Data on CSO water quality and the characteristics of CSO samples and discharges were obtained directly from each municipality, as indicated in Table 1. Most of the CSO water quality data were obtained in electronic format from the originators of the data. Each data set, as received, had already been validated according to data quality objectives established by each agency. Each data point was considered usable by the originators of the data; therefore, no additional validating or censoring of data took place for this project.

Table 1. Data sources for water quality, sample, and discharge characteristics

Municipality	Number of CSOs	Date range	Reference
King County	12	1986 – 1992	Brown and Caldwell (1995); Mickelson pers. comm. 1999b
	4	1994 – 1995	Gurkewitz pers. comm. 1999
	5	1996 – 1997	King County DNR (1999); Mickelson pers. comm. 1999a
City of Bremerton	14	1996 – 1997	Fohn (1997)
Greater Vancouver Regional District	8	1993 – 1996	Lee (1998); MacDonald pers. comm. 1999a
	6	1997 – 1998	MacDonald pers. comm. 1999b

The percent sewage in the CSO discharge was intended to be a surrogate for the duration of the discharge event, because duration information was not available for all events. The percent sewage was calculated, when possible, by evaluating the concentrations of sewage tracers such as ammonia and caffeine in the CSO discharge. Both ammonia and caffeine are always present in sewage, but are found in very low or undetectable concentrations in stormwater.

Percentages of sewage for a particular event were calculated by dividing the concentration of the tracer (ammonia for GVRD and Bremerton, caffeine for King County) measured in the discharge by a mean sewage influent tracer concentration calculated for a relatively dry winter month. The concentration of the tracer in stormwater was assumed to be zero. For Bremerton, the sewage ammonia concentration used in the calculations was 17.6 mg/L, which was the mean concentration from the Bremerton Wastewater Treatment Plant (WWTP) for March 1996 (Fohn 1997). For GVRD, two different concentrations were used because two WWTPs contribute to the CSOs under consideration. For the Vancouver Sewerage Area, which is serviced by the Iona Island WWTP, and the Fraser Sewerage Area, which is serviced by the Annacis WWTP, the mean concentrations for February 1997 (11 and 15 mg/L, respectively) were used (MacDonald pers. comm. 1999c). All the CSOs under consideration fall within the Vancouver Sewerage Area except for Glenbrook and Westridge, which fall within the Fraser Sewerage Area. For King County, the mean caffeine concentration used was 67.7 mg/L, which is a representative concentration according to the Water Pollution Control Division of King County (Mickelson pers. comm. 1999b).

Rainfall records were reviewed for the days prior to each discharge event compiled in the CSO water quality database. A storm-free day was considered to be a day with measured rainfall less than 0.05 inches (Tasker and Driver 1988). This interpretation of “storm-free” was made to distinguish very light rain events that are less likely to flush accumulated contaminants from impervious surfaces. Daily rainfall data were obtained from the National Weather Service (http://www.seawfo.noaa.gov/). The following stations were used: BLAIN (located in Blaine, WA) for GVRD, BREMT (located in Bremerton, WA) for Bremerton, and SEUW1 (located at the University of Washington) for both Seattle and King County.

A simplified description of land use was developed for this project. Land use was divided into residential, industrial, and commercial categories. Percentages for each drainage basin in Bremerton and Vancouver were derived from Fohn (1997) and Lee (1998), respectively. Vancouver land-use information was obtained from an analysis of digitized aerial photos by the geographical information system (GIS) group at the Greater Vancouver Sewerage and Drainage District (Lee 1998). Bremerton land-use percentages were also derived from a review of aerial photos. The accuracy of the estimates is likely to be less than Vancouver’s estimates because GIS was not used.

For King County and Seattle, a comprehensive review of local attempts to delineate drainage basins was conducted. After reviewing available information, a database generated by the King County Department of Natural Resources (King County DNR) Wastewater Treatment Division (formerly known as Metro) was selected. While this database represents an appropriate spatial scale and content, it is not without flaws. Because all pipes and flows lead to a treatment center, water from one basin may be en route to a plant when flow capacity is reached and an overflow event occurs. Therefore, the chemical signature of a CSO in a basin is not necessarily representative of runoff from that basin.

Two possible land-use categorizations (LUCs) were studied. The first scheme, based on work by Chandler (1995), is defined as follows:

LUC1

IND: >75% industrial	COMM: >75% commercial
RES: >75% residential	MIXED: none of the above

The second LUC combines some of the category definitions and eliminates the MIXED category. This classification scheme, based on empirical observation of ranges of land use, both in Seattle and the other municipalities, is defined as follows:

LUC2

IND: >50% industrial
RES: >50% residential, <10% industrial, <10% commercial
RI (residential/industrial): >50% residential, >10% industrial, industrial>commercial
RC (residential/commercial): >50% residential, >10% commercial, commercial>industrial
COMM: >50% commercial

The potential applicability of each LUC scheme for Seattle’s CSOs was evaluated by assessing the number of Seattle CSO drainage basins that would be placed in each category and the number of CSO drainage basins and discharge events that would be placed in each category for the three municipalities in the CSO water quality database.

Under both schemes, the land use for Seattle CSO drainage basins is dominated by the residential category, with lesser amounts of the industrial and commercial categories. Using either LUC scheme, all the industrial and commercial CSOs are in King County. Given the similarity of the data for the two LUC schemes, either one would be suitable for the required analyses. All subsequent analyses were conducted using LUC2 because it better represented land use in the Seattle drainage basins and eliminated the ambiguous MIXED category.

Statistical Methods

The objective of this project was to estimate the range of likely chemical concentrations within CSOs for all types of storm events that cause an overflow. The analysis focused on the one variable that is consistent across storm events: land use. Concentrations were compared among land-use categories; categories were combined when no differences were observed.

To calculate typical chemical concentrations for each CSO, individual discharge events were treated as replicate observations of chemical concentrations for the CSO. To reduce the effect of differences among sampling methods, only sequential or flow-weighted composite samples that included the first flush were used in this analysis. Multiple composites for the same storm event at the same CSO were averaged. Chemical concentrations reported as less than the method detection limit (MDL) are included at half the MDL.

Chemistry data were graphically evaluated for normality and symmetry using histograms and boxplots. The distributions of chemical concentrations were positively skewed, with the exception of the distribution of dissolved zinc, which exhibited approximate normality, so the median was selected as an appropriate measure of central tendency for prediction. Concentrations of all chemical except dissolved zinc were log-transformed (base 10) to approximate normality in the data distribution.

Statistical comparisons were used to identify which land-use groups had statistically similar chemical concentrations. Land-use groups that had similar concentrations were pooled to provide a larger data set from which predictions could be made. The median concentrations from these pooled samples were used to estimate loading for each Seattle CSO. The pair-wise comparison procedure used was Fisher’s least significant difference (LSD) test, performed on rankit-transformed data. To ensure a higher statistical power (i.e., detecting a difference if one exists), the alpha level was set at 0.10 for each comparison.

Relationships among residuals from the land-use analysis and data source, time, days since rain, and percent sewage were explored graphically using scatter plots and boxplots. Residuals were calculated by subtracting the mean of the log-transformed concentrations for each land-use group from the log-transformed concentration data. The land-use groups referred to here have been combined to reflect the groups identified as similar for each chemical in the preceding analysis.

Results and Discussion

Substances of Concern

More than 280 substances were measured in CSO samples compiled in the CSO water quality database. Many of these substances were detected infrequently or not at all. To focus the statistical analyses, a smaller set of substances was selected for further analysis. The primary criteria for selecting these substances were frequency of detection and an analysis of concentrations in CSO discharges relative to aquatic life criteria and ambient water quality. For substances without aquatic life criteria, e.g., hydrocarbons, conclusions regarding chemicals of concern from other local studies of CSO or stormwater quality were reviewed. In many cases, these conclusions were based on comparisons of chemical concentrations in stormwater or CSO discharges to toxicity data from scientific literature.

Table 2 presents summary statistics for the most frequently detected substances in the CSO water quality database. Frequently detected substances included trace elements, several polycyclic aromatic hydrocarbons (PAHs), bis(2-ethylhexyl)phthalate (BEHP), and bacteria.

Table 2. Statistics for frequently detected substances in CSO water quality database

Analyte	Units	Number of Samples Analyzed	Number of Detected Values	Average of Detected Values	Maximum Detected Value	Minimum Detected Value
Zinc	**mg/L**	**259**	**259**	**0.13**	**0.828**	**0.01**
Copper	**mg/L**	**261**	**257**	**0.05**	**0.36**	**0.004**
Lead	mg/L	259	245	0.03	0.34	0.002
Chromium	mg/L	256	224	0.01	0.47	0.001
Arsenic	mg/L	250	206	0.003	0.0122	0.0005
Nickel	mg/L	227	157	0.02	1.11	0.001
Cadmium	mg/L	244	153	0.001	0.014	0.0001
BEHP	**μg/L**	**146**	**132**	**10.26**	**135**	**1**
Fluoranthene	**μg/L**	**172**	**118**	**0.42**	**5.5**	**0.02**
Phenanthrene	**μg/L**	**171**	**125**	**0.41**	**3.5**	**0.03**
Antimony	mg/L	188	124	0.002	0.00474	0.0003
Fecal coliform bacteria	**colonies/ 100 mL**	**96**	**96**	**1,131,042**	**8,000,000**	**30,000**

NOTES: Analytes in bold were selected as substances of concern
All metals concentrations are total metals

Total copper and total zinc have been frequently identified as substances of concern in stormwater characterizations (e.g., Herrera and others 1994). The average total concentrations for these two metals in stormwater were higher than acute aquatic life criteria, although such criteria are based on the dissolved form rather than the total form. In spite of the metals loading from wet-weather flows, no water quality problems attributable to copper and zinc have been identified in Seattle receiving water bodies. For example, concentrations of copper and zinc in bimonthly samples from the Duwamish River did not exceed applicable criteria (Ecology 1994). Nevertheless, because of the wide distribution of these toxic metals in urban areas, copper and zinc were considered substances of concern.

Hydrocarbons are widespread in urban settings and are frequently detected in both stormwater and CSO samples. Generic analyses of hydrocarbons in environmental samples are typically reported as oil and grease and/or total petroleum hydrocarbons (TPH). Less than 15% of the samples in the database were analyzed for these substances. The most toxic components of TPH are thought to be PAHs, which were measured more frequently than oil and grease or TPH. PAHs are organic pollutants of concern in both stormwater and CSOs (Herrera and others 1994). The two most frequently detected PAHs in this data set, phenanthrene and fluoranthene, were selected as substances of concern. These two PAHs were used as surrogates for all hydrocarbons.

The most frequently detected organic compound after fluoranthene and phenanthrene was BEHP. Phthalates are a concern in both stormwater and CSOs (Herrera and others 1994). This particular phthalate is of particular concern in Duwamish River sediments, where it has been identified as a primary contaminant of concern (King County DNR and others 1997; Romberg pers. comm. 1999). This compound has also been detected at concentrations of concern in the sediment at many other locations in Puget Sound. A recent summary of Puget Sound sediment data indicated that 20%of the measured concentrations of this compound might be associated with possible adverse effects to aquatic life (EPA 1997). This compound was added to the list of substances of concern.

Fecal coliform bacteria are often monitored in stormwater and CSO sampling programs. A recently conducted study of CSOs in the Duwamish River and Elliott Bay identified risks from CSO viruses to people who swim during or immediately after a CSO event (King County DNR 1999). Interpretation of bacteria data is difficult, given variability that can range over several orders of magnitude and the uncertain relationship between fecal coliform bacteria, which can come from any warm-blooded animal, and pathogenic viruses associated with human sewage. Sources of variability include physical factors within the receiving water (Canale and others 1993; Gannon and others 1983; Irvine and Pettibone 1993), bacterial die-off rates (Bravo and deVicente 1992), episodic events such as storms and recreational activities, and the lack of routine replicate analyses (Fleisher 1985). Fecal coliform bacteria are considered substances of concern, but for the reasons outlined above, assessment of impacts was done qualitatively rather than using a statistical analysis as was done for the other substances of concern.

Land Use

Figure 1 displays the effect of land use on the concentrations of the five chemical substances of concern, including both total and dissolved copper and zinc. Total copper concentrations in residential/commercial (RC) areas (Group A in Table 3) were lower than in industrial, residential, and commercial areas (Group B in Table 3). Concentrations in residential/industrial (RI) areas were similar to both groups of land-use categories, so the median concentration for RI groups was estimated separately.

Within the Lake Union basin, concentrations of metals, including copper, have been associated with industrial and high-density residential land-use categories (Herrera and others 1994). The findings presented in Table 3 show a slightly different picture. The mean and median total copper concentrations for the RC category (roughly equivalent to high-density residential land use) were lower than for all other categories. Industrial CSOs have total copper concentrations similar to residential and commercial CSOs, although the maximum concentration is much lower for the commercial land-use category.

Dissolved copper was only measured at King County sites (33 discharge events), but the median concentration at the commercial CSO (King St.) was significantly higher than the median concentration for the residential/industrial CSO (Chelan), and both of these were significantly higher than the industrial CSOs (Hanford, Brandon, and Connecticut)(Table 3).

Zinc concentrations were highest at the industrial and commercial sites (Table 4). Other groupings were uncertain, so they were treated individually for estimating discharge concentrations. Within the Lake Union basin, concentrations of heavy metals, including zinc, have been associated with industrial and high-density residential land-use categories (Herrera and others 1994). The results presented above also indicate that the highest concentrations were found in industrial and commercial areas, but concentrations in the RC category (roughly equivalent to high-density residential land use) were approximately one-half the concentrations found in industrial and commercial areas.

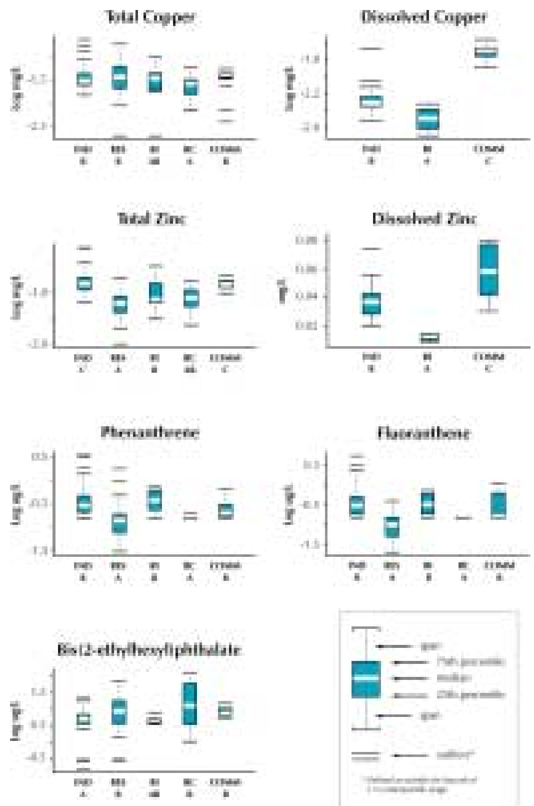

Figure 1. Boxplots of log-transformed (base 10) chemical concentrations plotted versus land use groupings. Common letters indicate non-significant differences, based on Fisher's LSD test (= 0.10)

Table 3. Copper concentrations (mg/L) by land-use category

Chemical	Land-Use Category	n	Mean	Median	75th Percentile	Maximum	Multiple Comparison Results[A]
Total copper	IND	63	0.044	0.031	0.044	0.24	B
	RES	59	0.050	0.037	0.063	0.20	B
	RI	16	0.041	0.035	0.045	0.10	AB
	RC	17	0.027	0.027	0.033	0.059	A
	COMM	16	0.038	0.043	0.045	0.057	B
Dissolved copper	IND	22	0.0059	0.0049	0.0057	0.021	B
	RES	0	na	na	na	na	na
	RI	4	0.0033	0.0032	0.0039	0.0048	A
	RC	0	na	na	na	na	na
	COMM	7	0.020	0.021	0.022	0.027	C

NOTE: n - number of discharge events for which total copper was measured
[a] Common letters indicate non-significant differences, based on Fisher's LSD test ($\alpha = 0.10$). Multiple comparisons were performed separately for total and dissolved copper

Industrial, RI, and commercial areas had higher median concentrations of phenanthrene and fluoranthene than residential or RC areas (Table 5). Within the Lake Union basin, concentrations of PAHs have been associated with commercial and high-density residential land use categories (Herrera and others 1994). Concentrations of phenanthrene at commercial sites were higher than concentrations at most residential sites, but lower than concentrations at industrial or residential-industrial sites. Fluoranthene concentrations at industrial sites or sites with an industrial component (i.e., RI) were higher than concentrations at sites in other land-use categories (Table 5).

Table 4. Zinc concentrations (mg/L) by land-use category

Chemical	Land-Use Category	n	Mean	Median	75th Percentile	Maximum	Multiple Comparison Results[A]
Total zinc	IND	63	0.175	0.14	0.19	0.71	C
	RES	59	0.069	0.06	0.081	0.19	A
	RI	16	0.11	0.071	0.14	0.32	B
	RC	17	0.084	0.077	0.11	0.16	AB
	COMM	16	0.145	0.14	0.16	0.21	C
Dissolved zinc	IND	22	0.037	0.037	0.042	0.074	B
	RES	0	na	na	na	na	na
	RI	4	0.012	0.013	0.014	0.015	A
	RC	0	na	na	na	na	na
	COMM	7	0.059	0.058	0.075	0.08	C

NOTE: n - number of discharge events for which total zinc was measured
[a] Common letters indicate non-significant differences, based on Fisher's LSD test ($\alpha = 0.10$). Multiple comparisons were performed separately for total and dissolved zinc

Residential, commercial, and RC areas had higher median concentrations of BEHP than industrial areas (Table 5). RI areas were similar to both groups, so they were estimated individually. The results of the land-use analysis are consistent with a recent Lake Union study of stormwater quality, which indicated that phthalates were highest in areas of high-density residential land uses (Herrera and others 1994). In this study, the mean, median, 75th percentile, and maximum concentrations were much higher in the RC category than for the other land-use categories (Table 5).

Table 5. Concentrations (µg/L) of organic compounds by land-use category

Chemical	Land-Use Category	n	Mean	Median	75th Percentile	Maximum	Multiple Comparison Results[A]
Phenanthrene	IND	42	0.54	0.29	0.47	3.5	B
	RES	32	0.22	0.14	0.19	1.8	A
	RI	7	0.42	0.38	0.59	0.73	B
	RC	8	0.16	0.15	0.15	0.2	A
	COMM	15	0.29	0.20	0.27	0.69	B
Fluoranthene	IND	42	0.63	0.31	0.51	5.5	B
	RES	34	0.13	0.10	0.15	0.4	A
	RI	7	0.41	0.32	0.57	0.75	B
	RC	8	0.15	0.15	0.15	0.15	A
	COMM	15	0.36	0.16	0.48	1.1	B
BEHP	IND	42	5.6	5.0	6.7	22	A
	RES	16	14	8.7	18	72	BC
	RI	7	4.8	4.9	5.0	7.75	AB
	RC	8	40	15	53	135	BC
	COMM	15	8.4	7.2	10	15	BC

NOTE: n - number of discharge events for which compound was measured
[a] Common letters indicate non-significant differences, based on Fisher's LSD test (α = 0.10). Multiple comparisons were performed separately for each compound

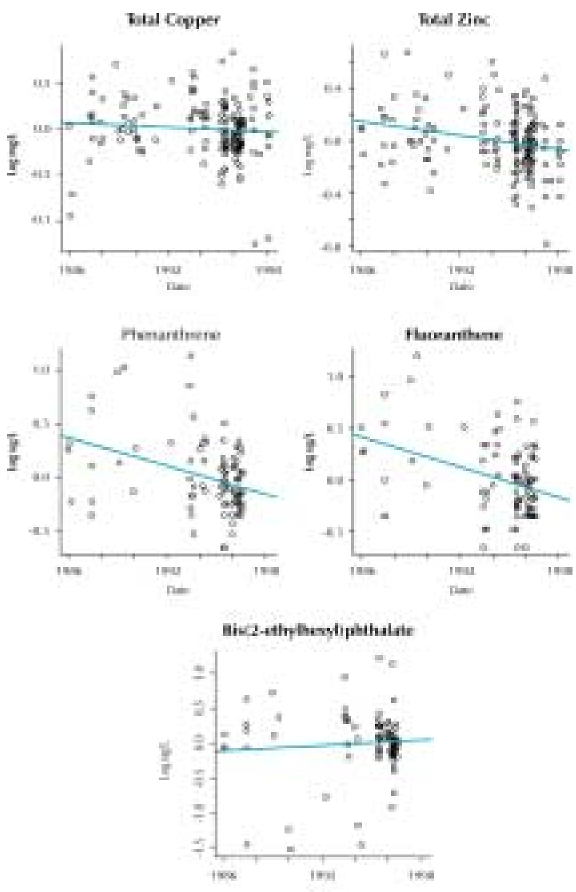

Figure 2. Log-transformed (base 10) chemical concentrations plotted by date; least squares linear trend lines added for reference

Date

Sampling dates included in the CSO water quality database range from 26 October 1986 to 27 December 1998, with 70% of the measured storm events occurring since 1995. Figure 2 displays the residuals from the land-use analysis plotted against time. Based on limited data prior to 1995, concentrations of total zinc, fluoranthene, and BEHP may have decreased. The visual trend is confirmed with significant correlation for these three chemicals (Pearson's correlation test, $p<0.05$). This result is not conclusive evidence that decreasing trends are present in CSO discharges in this region; many factors have not been considered, including seasonal fluctuations. However, there is no evidence that concentrations of these chemicals are increasing.

Percent Sewage

The percent sewage in the CSO discharges included in the CSO water quality database was estimated using the tracers caffeine or ammonia. In all, 125 estimates were made. Summary statistics for this variable are presented in Table 6. Figure 3 shows the land-use residuals plotted against log-transformed estimated percent sewage. Exploratory analysis of the percent sewage estimates indicates that copper and zinc show signs of increasing with an increase in the percent sewage. This observation is confirmed with significant positive correlation between percent sewage and copper and zinc concentrations (both log-transformed, Pearson's correlation test, $p<0.05$). The implication of this finding for Seattle loading estimates is difficult to judge, since the percent sewage in Seattle CSOs is unknown. The total copper loading may be underestimated if a high percentage of overflows have a high sewage percentage (greater than 30 percent, for example).

Table 6. Percent sewage estimates for CSO discharge events in King County, Bremerton, and Vancouver, BC

Municipality	n	Mean	Median	Minimum	Maximum
King County	50	17.2	11.5	2	90
Bremerton	25	13.5	7.0	1	63
Vancouver	50	18.8	12.5	1	70
All	125	17.1	10	1	90

Days Since Rain

Since many discharge events were associated with multi-day storms, there were often (59%) no dry days prior to the time the discharge occurs. One or more days of dry weather (i.e., less than 0.05 inches of measured rainfall) were associated with the remaining 41% of the discharge events. In Figure 4, the land-use residuals are plotted against the number of days since the last rainfall. There was some indication that an increase in copper and zinc may occur when there have been more than three days between rainfall events. The implication of this finding for Seattle is that the total copper and zinc loading for discharges after more than three dry days may be underestimated. For example, the median total copper concentration in the residential land-use category for discharges after more than 3 days without rain was 0.13 mg/L, compared to a median of 0.034 mg/L for all events in the residential category. The median total zinc concentration in this category was 0.12 mg/L, compared to a median 0.06 mg/L for all events in the residential category. However, there were only four discharges in this category, all from the GVRD study, and they all followed more than 5 dry days.

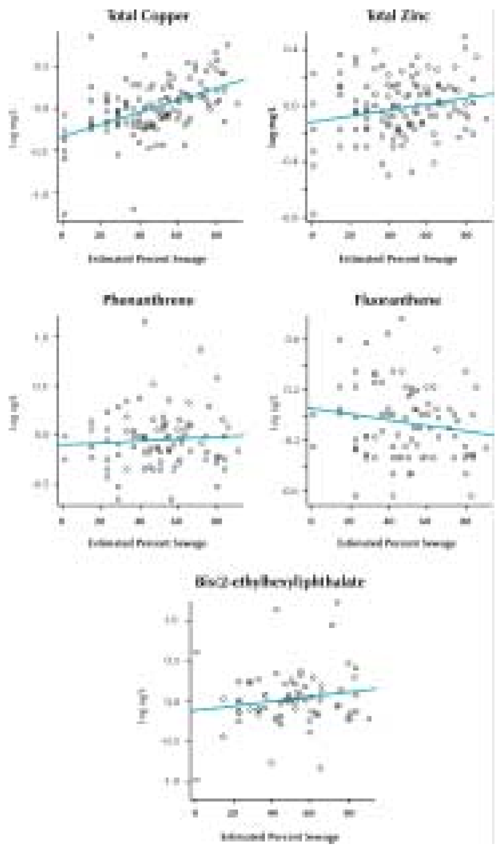

Figure 3. Log-transformed (base 10) chemical concentrations plotted against estimates of percent sewage; least squares linear trend lines have been added for reference.

Comparison to Water Quality Criteria

Concentrations from the CSO water quality database were compared to applicable water quality criteria (WQC) or guidelines. This comparison was intended to identify substances that could be further evaluated in the receiving water to assess the likelihood that adverse effect to aquatic life and or human health may occur.

Copper—Local studies of stormwater and CSO water quality generally conclude that copper is a substance of concern because concentrations in the discharges tend to exceed acute water quality criteria (e.g., Fohn 1997; Herrera and others 1994; Lee 1998). Table 7 lists the number of discharge events for which dissolved copper and zinc WQC were exceeded.

Exceedances of copper WQC were noted for some samples from industrial sites, all samples from commercial sites, and none of the samples from RI sites. The median, 75th percentile, and maximum dissolved copper concentrations from the commercial sites (0.021, 0.022, and 0.027 mg/L, respectively; Table 3) all exceeded the acute criterion by a factor of at least three.

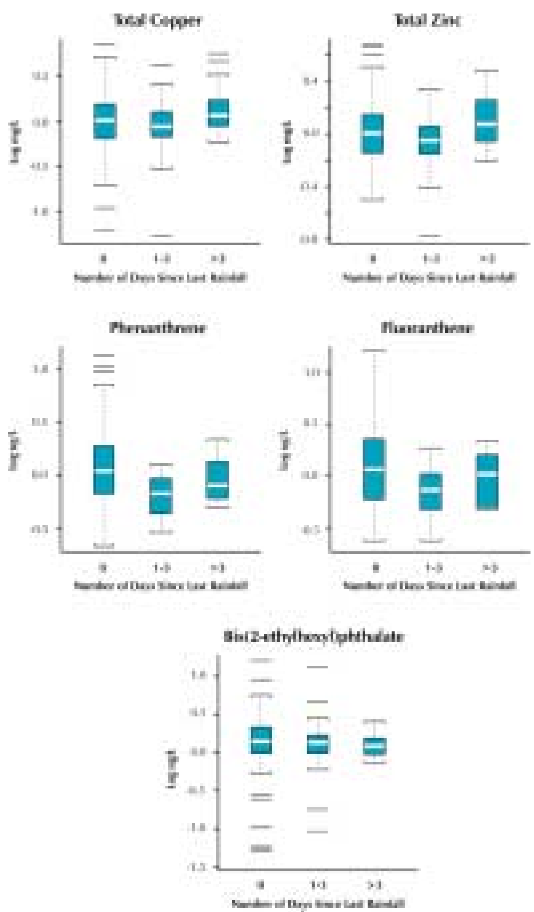

Figure 4. Boxplots of log-transformed (base 10) chemical concentrations plotted against the number of days since the last rainfall

Table 7. Frequency of exceedance of Washington WQC by concentrations of dissolved copper and zinc in King County CSOs

Land-Use Category[a]	Frequency of Exceedances			
	Dissolved Zinc		Dissolved Copper	
	Freshwater Acute Criterion (0.0527 mg/L)	Marine Acute Criterion (0.090 mg/L)	Freshwater Acute Criterion (0.0072 mg/L)	Marine Acute Criterion (0.0048 mg/L)
IND	2 of 22	0 of 22	3 of 22	11 of 22
RES	nd	nd	nd	nd
RI	0 of 4	0 of 4	0 of 4	0 of 4
RC	nd	nd	nd	nd
COMM	5 of 7	0 of 7	7 of 7	7 of 7

NOTE: nd - no data
Freshwater criteria calculated assuming a hardness of 40 mg/L

Very few data for dissolved copper were available for residential areas. Only four samples from one partially residential CSO were included in the CSO water quality database, and this CSO is classified as RI (53%residential, 45% industrial). Total copper was measured much more frequently (92 samples from the three residential categories), but WQC are based on the dissolved fraction, not the total metal concentration. The dissolved copper fraction is not consistent for the King County matched samples. However, assuming the relationship between land use and dissolved copper fraction holds for Seattle CSOs, the best estimate of the fraction for most Seattle CSOs is the mean of the fraction for the 4 RI samples. This fraction (mean 0.15, range 0.06 to 0.27) was used to predict dissolved copper for the Seattle CSOs in residential areas.

Application of the dissolved copper fraction to the total copper data summarized in Table 3 results in estimated summary statistics displayed in Table 8. These rough estimates indicate that some exceedances of WQC are to be expected in the Seattle residential land-use areas. The median of the estimated dissolved copper concentrations was very close to the marine acute criterion for all three residential categories. However, the estimated dissolved copper concentrations for the RI category were much higher than those observed for King County CSOs (Table 3). Given the uncertainty around the fraction of dissolved copper, no estimate of the frequency of expected exceedances was made.

Table 8. Estimated summary statistics for dissolved metals (mg/L) in unmeasured land-use categories

LUC2	Mean	Median	75th Percentile	Maximum
Copper				
RES	0.0075	0.0056	0.0095	0.029
RI	0.0061	0.0053	0.0068	0.015
RC	0.0041	0.0041	0.005	0.0089
Zinc				
RES	0.0097	0.0084	0.011	0.027
RI	0.015	0.0099	0.02	0.044
RC	0.012	0.011	0.015	0.022

NOTE: Acronyms defined in Section 3.2.4

Zinc—Next to copper, zinc has been shown to exceed WQC most frequently in both stormwater and CSOs (e.g., Fohn 1997; Herrera and others 1994; Lee 1998). The data in Table 7 indicate that the dissolved zinc concentration exceeded the dissolved freshwater acute criterion some of the time, but never exceeded the marine acute criterion. The median, 75th percentile, and maximum dissolved zinc concentrations from the commercial sites (0.058, 0.075, and 0.080 mg/L, respectively; Table 4) all exceeded the freshwater acute criterion.

An estimate for the fraction of dissolved zinc was derived as for copper. The zinc fraction (mean 0.14, range of 0.06 to 0.22) was very similar to the copper fraction. Application of the dissolved zinc fraction to the total zinc data summarized in Table 4 results in the summary statistics displayed in Table 8. These rough estimates indicate that no exceedances of zinc WQC would be expected in the residential areas.

Phenanthrene—The State of Washington has no criterion for this compound, but EPA (1994) has proposed an acute criterion of 30 μg/L for fresh water and 7.7 μg/L for marine waters. The maximum concentration presented in Table 5 (3.5 μg/L from an industrial site) is lower than these proposed criteria, so no adverse impacts to aquatic biota would be expected from this compound in Seattle CSOs.

Fluoranthene—The State of Washington has no criterion for this compound, but EPA (1994) has compiled lowest observed adverse effects levels (LOAELs) that could serve as guidelines until criteria are adopted. The LOAEL for freshwater is 3,980 μg/L and the LOAEL for marine waters is 40 μg/L. The maximum concentration in Table 5 (5.5 μg/L from an industrial site) is much lower than these LOAELs, so no adverse impacts to aquatic biota would be expected from this compound in Seattle CSOs.

Bis(2-ethylhexyl)phthalate—Although phthalates have been identified as potential substances of concern in sediments, particularly in the Duwamish River (King County DNR and others 1997; Romberg pers. comm. 1999), BEHP concentrations in the CSO water quality database compiled for this project were well below concentrations thought to be toxic to aquatic organisms. The State of Washington has no criterion for this compound, but EPA (1994) has proposed an acute criterion for both marine and fresh water of 400 μg/L. The maximum concentration presented in Table 5 (135 μg/L) is much lower than these proposed criteria, so no adverse impacts to aquatic biota in the water column would be expected from this compound in Seattle CSOs.

Discussion of Potential Impacts in Receiving Water

The results presented in above are illustrative of the magnitude of chemical concentrations in CSO effluent, but they are one step removed from the receiving water where potential impacts to aquatic biota and humans could occur. Of the five chemicals studied, only zinc and copper could potentially impact aquatic biota in receiving water bodies in Seattle. In addition, fecal coliform bacteria contained in the effluent may potentially impact the health of people who come in contact with it during recreational activities (King County DNR 1999). The discussion in this section will be primarily limited to these three substances.

Assessing the impacts of CSO discharges to receiving water is complicated by the episodic nature of the discharge events. Assessments based on concentrations in the water are meaningful only if the impact of a CSO discharge is captured in the samples. Samples collected during the dry season or weeks after the most recent discharge are unlikely to reflect the impact of CSO discharges. King County DNR (1999) has conducted the only study to date in this region that has attempted to characterize CSO impacts to receiving water before, during, and after discharges. Other than data collected in the above study for the Duwamish River and Elliott Bay, chemistry data are very limited for other receiving water bodies in Seattle.

During the King County DNR (1999) study, weekly water samples during non-discharge conditions were collected at five different CSOs in the Duwamish River and the Seattle waterfront over a 9-month period during 1996-1997. Samples were collected from surface and near-bottom depths at three locations: adjacent to the east and west banks, and in the center of the waterway. Samples were collected approximately 50 ft from the outfall. Following four storm events during which the major CSOs in the study discharged, daily samples were collected for three days following the onset of the discharge. The data collected from this study served as input to a hydrodynamic model intended to evaluate the impact of CSOs on receiving water quality.

The water samples were analyzed for arsenic, cadmium, copper, lead, nickel, and zinc; organic compounds; and fecal coliform bacteria. Organic compounds were almost never detected and will not be discussed further. For most of the metals measured in the receiving water during the King County DNR (1999) study, the range of concentrations during non-discharge conditions was relatively small (approximately ∀ 2X the mean). For some metals, elevated concentrations were clearly evident following discharge events. The magnitude of the elevation was approximately 2X for most metals, although it was not evident in many cases. In spite of the observed “spikes” attributable to CSO discharges, none of the metal concentrations measured following these events exceeded marine acute water quality criteria.

Three of the CSOs included in the above study—Connecticut, Brandon, and Hanford—are among the largest in volume in the King County system, and are much larger than any Seattle CSO. The mean concentrations of copper and zinc in the effluent from these CSOs are higher, particularly for Brandon and Connecticut, than the mean concentrations for most of the other CSOs in the database compiled for this project. Therefore, the loading of copper and zinc from Seattle CSOs is unlikely to exceed the loading from the CSOs mentioned above. Except for Longfellow Creek, Seattle receiving water bodies other than those studied by King County DNR (1999) have adequate flushing characteristics and sufficient volume available for dilution. Consequently, for these water bodies, the elevation in ambient concentrations of copper and zinc in the receiving water following discharges from Seattle CSOs is unlikely to be greater than that observed in the King County DNR (1999) study. The volume available for dilution is much smaller in Longfellow Creek compared to other Seattle receiving water bodies. Although stream sampling has not been conducted during discharge events, the ambient concentrations of metals in Longfellow Creek have generally been well below acute aquatic life criteria (O’Laughlin pers. comm. 1999).

The sampling conducted in the Duwamish River and Elliott Bay for the King County DNR (1999) study confirmed that CSOs have contributed to elevated concentrations of fecal coliform bacteria (as high as 5,800 colonies/100 mL) during and immediately following discharge events. All measurements made during and following discharge events exceeded the threshold concentration of 43 colonies/100 mL contained in the State's marine water quality standard. However, modeling conducted by King County DNR using these data concluded that even in the absence of CSOs, water quality standards for fecal coliform bacteria would still be frequently exceeded in the Duwamish River and Elliott Bay (King County DNR 1999). This conclusion suggests that there are sources of bacteria other than CSOs.

A simple comparison of bacterial concentrations near CSOs to water quality standards does not constitute a comprehensive assessment of the potential for these discharges to adversely affect human health. Such an assessment would require an examination of the designated beneficial uses the standards are designed to protect, an evaluation of the potential human exposure scenarios near Seattle CSOs, and a determination of the suitability of the fecal coliform standard for predicting health effects to humans.

The beneficial uses the State's bacteria standards are intended to protect are shellfish harvesting and primary contact recreation (WAC 173-201A). All King County beaches are closed to recreational bivalve harvest (Washington State Department of Health 1999), but crab fishing does occur in some marine areas. Primary contact recreation includes activities such as swimming, scuba diving, and wind surfing. All these activities were evaluated in the human health risk assessment conducted by King County DNR (1999).

Although water-based recreational activities could potentially occur at any time of year in Seattle, they are likely to be more common during the summer months, when discharges are rare and relatively low in volume.[1] King County has recognized this pattern; they monitor bacterial concentrations at Lake Washington swimming beaches only from May through September. The human health risk assessment acknowledged seasonal differences in exposure, but did not attempt to quantify them (King County DNR 1999). State water quality standards for bacteria have also acknowledged seasonal differences in exposure. Six states and the District of Columbia have included provisions in which the numeric criteria for bacteria standards do not apply where CSOs and stormwater discharges are likely to result in violations (EPA 1998). Twenty-one states have seasonal standards that only apply during the swimming season (EPA 1998).

Fecal coliform bacteria are not considered toxic as a group, but are used as an indicator for pathogenic bacteria and other microorganisms toxic to humans such as viruses and protozoa. The suitability of fecal coliform bacteria as a water quality standard has been hotly debated nationwide. No consensus exists within state standards on which indicator is most effective. As of September 1997, the majority of states, including Washington, included fecal coliform bacteria in their water quality standards (EPA 1998). Eleven states and one territory adopted an *E. coli* standard for fresh water. Six states, one tribe, and one territory use enterococci as a standard for fresh water. Six states and one territory also use enterococci as a standard for marine waters.

The analytical methods used to quantify fecal coliform bacteria give highly variable results, even for replicate samples. Many sampling programs, including King County's swimming-beach monitoring program, collect only single samples per station per sampling event. Without an estimate of variability per sample, it is difficult to determine whether the standards[2] are being met. For example, a review of three years of monitoring data collected by the New York City Department of Health determined that 57% of the data were not significantly different from the standard being used. Therefore, the collection of these data represented a substantial waste of time and expense (Fleisher 1985). A bacteria-monitoring program must address these kinds of statistical considerations if determining compliance is the primary objective.

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[1] Approximately 6% of the discharges summarized in Table 2-2 occurred during the summers of 1997 and 1998 (Memorial Day through Labor Day). With the exception of a large storm event on 31 May 1997 that triggered 7 CSO discharges greater than 100,000 gallons, all these summer discharges were less than 100,000 gallons.

[2] The standard is based on the geometric mean of 5 or more samples collected over a 30-day period.

Conclusions

Collecting CSO chemistry data that adequately represent the temporal variability of a discharge event and the potential impact on a receiving water body is difficult and expensive. The data analyses conducted here suggest that on a programmatic basis the expected range of chemical concentrations in Seattle's CSO effluent can be predicted using regional CSO chemistry data and associated environmental variables, thereby saving the expense of implementing an extensive chemical monitoring program. The City of Seattle submitted a report based on these analyses to the Washington Department of Ecology in partial satisfaction of the City's NPDES permit requirement to characterize the CSS and its potential impacts to Seattle receiving water bodies.

Several significant relationships were identified between regional CSO chemistry data and associated environmental variables:

- Median concentrations of the five chemicals of concern varied significantly between some land use classes, but the range from low to high was generally less than a factor of three
- A temporal trend analysis showed no evidence that chemical concentrations in CSO discharges have been increasing over time
- Correlations were noted between copper and zinc concentrations in CSO effluent and the estimated percentage of sewage in the discharge
- Copper and zinc concentrations were higher in CSO discharges that followed multiple days without rain compared to discharges monitored in the middle of long storm events

The potential impact to receiving water bodies was evaluated by comparing measured chemical concentrations to state water quality criteria. Of the chemicals evaluated, only copper and zinc had the potential to exceed criteria at the end-of-pipe. Chemical concentrations in receiving water bodies are unlikely to violate criteria due to mixing and the large water volume available for dilution in most of Seattle's water bodies. Bacterial standards may be violated by CSO discharges, but the discharges are uncommon in the summer when the frequency of human exposure is high.

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